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Preconsolidation pressure and creep settlements – Estimations based on results of oedometer tests

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ABSTRACT: The paper describes results of geotechnical investigations carried out in order to estimate the state of consolidation in Holocene silt and clay sediments of unusual thickness. The clay and silt sediments are overlain by 30 meters of sand, sedimented within the latest 1000 years.

Results of oedometer tests with undisturbed samples have been analysed by means of different methods to determine the preconsolidation pressure.

An attempt is made to estimate the creep rates on the basis of AMS ^{14}C-datings of the sediments and a model for creep determination proposed by Moust Jacobsen.

1 INTRODUCTION

The top of Denmark is a spit, Skaw Spit (Skagen Odde), formed since the Weichselian Ice Age by marine sediments. The outermost part of the spit emerged during the latest few centuries.

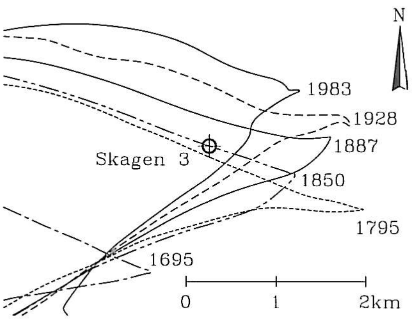

Fig. 1. The changing position of the northernmost coastline of the Skaw Spit (Hauerbach, 1992).

Levellings have indicated, that the youngest part of the spit does not follow the general geostatic uplift of the northern part of Denmark (Hauerbach, 1992).

Further, geological and geophysical investigations have indicated an unusual thickness of relatively young sediments (Knudsen, 1985, Lykke-Andersen, 1987).

In 1992 a boring, Skagen 3, was carried out at the very point of the spit, The Grenen Point. The boring was taken to a depth of 220 m and has shown 114 m of Holocene sediments underlain by sediments from Weichselian, Eemian, Saalian and Lower Cretaceous (Knudsen, 1994).

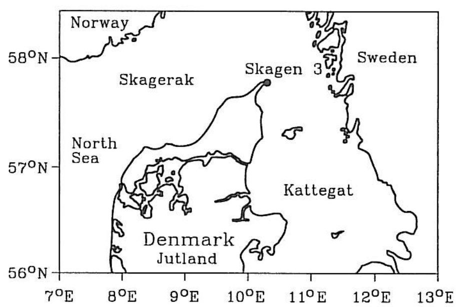

Fig. 2. The position of Skagen 3 boring.

The material from the boring is being studied as a research project by the GeoKat group at the Department of Earth Sciences, University of Aarhus in cooperation with "The Skagen Spit project -nature and culture", The Geological Survey of Denmark, The University of Quebec in Montreal, The University of Cambridge and Aalborg University.

One of the purposes of the geotechnical investigations presented in this paper has been to estimate the state of consolidation of the Holocene sediments.

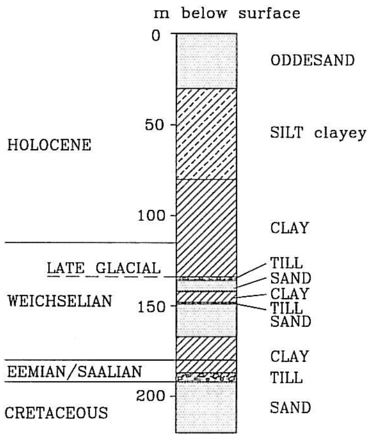

Fig. 3. Skagen 3 boring (Knudsen, 1994).

2. SAMPLING AND IN SITU TESTING

The Skagen 3 boring was, from the depth of 30 m, carried out as a rotary boring with continuous coring. In the Holocene silt and clay layers, undisturbed 70 mm diameter samples were extracted and vane tests carried out at 3 to 6 meters intervals.

In 1993 a boring, Skagen 4, through the upper 30 m "Odde"sand, was carried out as a cable percussion boring with continuous Split Spoon sampling.

In the Holocene clay sediments the undrained shear strength, c_v , measured by the vane represents values of 0.2 to 0.25 times the in situ pressure, σ'_o.

Based on the statistical relation $c_u/\sigma'_o = 0.11 + 0.0037\, I_P$, (Skempton, 1957), and the determined values of plasticity index, I_P, (chapt. 3), the results may indicate a clay in a normally consolidated state.

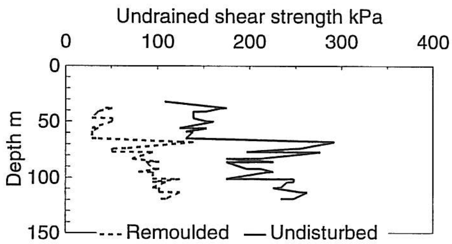

Fig. 4. Skagen 3 boring. Undrained shear strength measured by vane.

3. LABORATORY TESTING

Classification tests and oedometer tests have been carried out with the majority of the undisturbed samples from the Holocene sediments and also with a few samples of the cores from Weichselian and Eemian.

Results of the determination of water content, w, Atterberg limits, w_L and w_P, plasticity index, I_p, and organic content, O.C., are shown in Fig. 5.

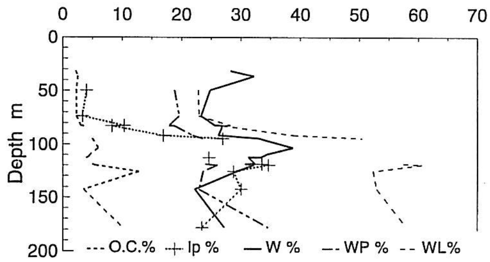

Fig. 5. Skagen 3 boring. Water content, Atterberg limits, plasticity index and organic content.

The oedometer tests have been carried out with 60 mm diameter samples in The Danish Consolidation Apparatus, which has a floating ring (Moust Jacobsen, 1967). The registration of the deformations during the tests has been automatic and continuous using transducers with an accuracy of 10^{-3} mm. The main results of the oedometer tests are given in fig. 6.

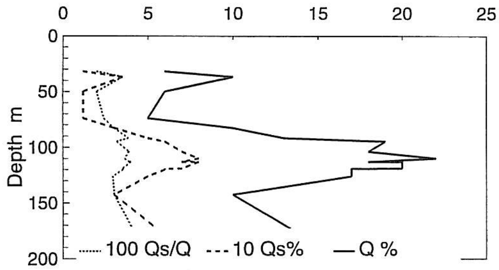

Fig. 6. Skagen 3 boring. Results of oedometer tests.

$Q = \frac{C_c}{(1+e_0)}$, C_c is the coefficient of compressibility

$Q_s = d\varepsilon/d\log t$, the creep rate for a soil in a normally consolidated state.

The values of Qs/Q correspond to the values found by Mesri (Mesri, 1987).

For the Holocene clay the coefficient of consolidation, c_k , has been determined to $4-8\times10^{+8} m^2/\sec$.

4. DETERMINATION OF PRECONSOLIDATION PRESSURE FROM OEDOMETER TESTS

On the basis of the oedometer tests the preconsolidation pressure of the soil has been determined using methods as suggested by Casagrande, Akai, and Christensen and Janbu.

4.1 *Casagrande's method*

For many years the method described by Casagrande (Casagrande, 1936) has been commonly used for the determination of the preconsolidation pressure from results of oedometer tests.

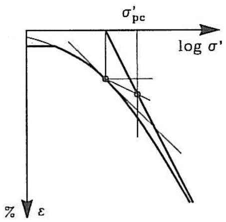

Fig. 7. Casagrande's method.

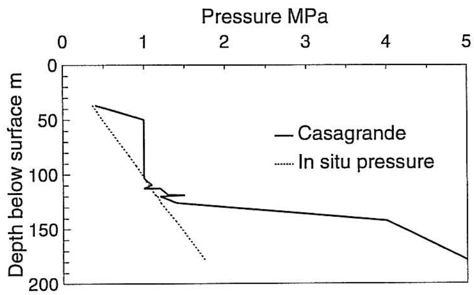

Fig. 8. Skagen 3 boring. Determination of σ'_{pc} by Casagrande's method.

4.2 *Akai's method*

Akai (Akai, 1960) has used the variation in the creep rate to determine the preconsolidation pressure.

A time settlement curve from a loading can be divided into a consolidation phase and a creep phase. The creep is assumed to be logarithmic by time having a creep rate of ε_s.

Akai discovered, that the rate of creep increased proportionally with the effective stress, σ', for $\sigma' < \sigma'_{pc}$ and with $\log \sigma'$ when $\sigma' > \sigma_{pc}$.

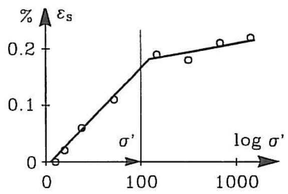

Fig. 9. Akai's method.

In the actual tests ε_s has proved to be nearly constant, Q'_s, for $\sigma' > \sigma'_{pc}$.

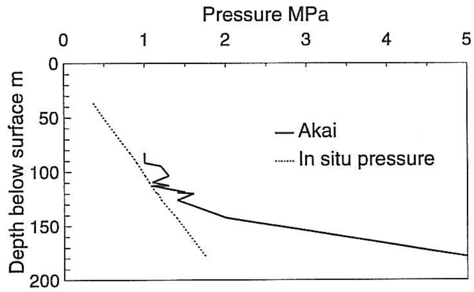

Fig. 10. Skagen 3 boring. Determination of σ'_{pc} by Akai's method.

4.3 *Christensen and Janbu's methods*

Christensen and Janbu (Christensen and Janbu, 1992), have suggested two methods to determine the preconsolidation pressure.

1) It is possible to determine the preconsolidation pressure from the variation in the Modulus K = $d\sigma'/d\varepsilon$. For a preconsolidated soil the modulus is nearly constant and for a normally consolidated soil the variation in the modulus is linear to the stress. It is therefore possible to determine σ'_{pc} at the break in the curve for modulus against stress.

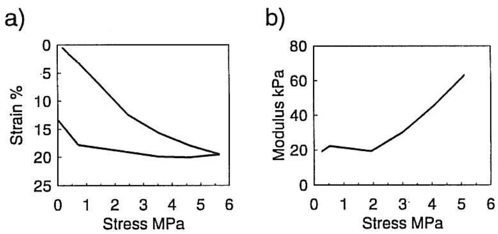

Fig. 11. Skagen 3 boring. Holocene clay. Curves for a) stress - strain b) modulus-stress.

2) The time resistance R = $dt/d\varepsilon$ from a time-settlement curve plotted against time will after some time show a linear curve. The inclination of this line r = dR/dt against stress for each load step will show a break in the curve at σ'_{pc}.

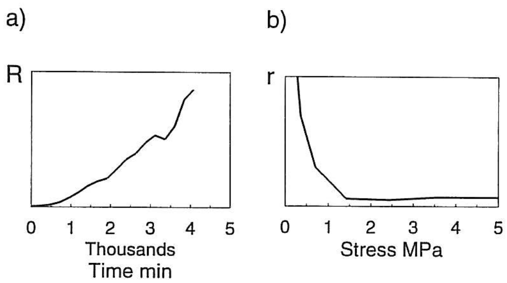

Fig. 12. Skagen 3 boring. Holocene clay. Curves for a) R against time b) r against stress.

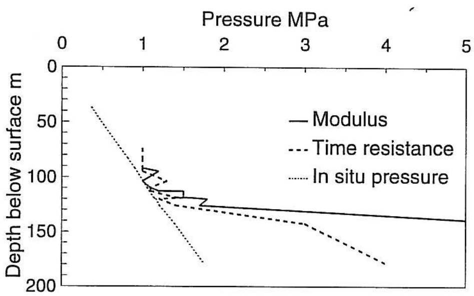

Fig. 13. Skagen 3 boring. Determination of σ'_{pc} by Christensen and Janbu's methods.

4.4 *Results of the determination of* σ'_{pc}

The results of the determinations of the preconsolidation pressures as described above indicate the overconsolidation ratio for the Late Glacial and Holocene clays to be $OCR \geq 1$.

In a stepwise oedometer test carried out on samples with in situ pressures as high as in the actual case, it is difficult to determine the correct value of σ'_{pc} because of the size of the load increment in each step. The scattering in the values determined may therefore represent the uncertainties in the determinations rather than variations in the preconsolidation pressures.

The boring has shown clay from 80 m to 134 m, which means a maximum drainage path of 27 m. On the basis of the determined coefficient of consolidation, c_k, the corresponding time of consolidation is 500 - 1000 years.

In the Late Glacial sediments sand and silt stribes have been observed, which may reduce the drainage path to 17 m and the time of consolidation to 200 - 500 years.

The results of the oedometer tests have indicated that the consolidation process in the Holocene and Late Glacial sediments, caused by the sedimentation of the "Odde"sand, is completed. Based on this it is concluded, that the drainage path must be smaller than half the total thickness of the clay sediments and that the sedimentation of the "Odde"sand must have been nearly finished some hundred years ago.

For the sample extracted just below the upper till layer and for the sample from Eemian the preconsolidation pressures have been determined to more than 2000 kPa and more than 4000 kPa, respectively, corresponding to OCR ≥ 1.4 and OCR ≥2.3.

5. AGE OF THE SEDIMENTS IN SKAGEN 3

Samples of foraminifera and shells from the marine sediments have been radiocarbon dated by the Accelerator Mass Spectrometry (AMS), (Nielsen et. al.,1994). Results from these datings have shown the age of the Holocene clay and silt sediments to be about 12.000 years in 114 m, about 6.000 years in 80 m and about 1000 years in 30 m below the surface.

The rate af sedimentation has been rather uniform, until the start of the sedimentation of the "Odde"sand.

Fig. 14. shows the max. and min. values of the datings from the "Odde"sand. In the upper 12 m of the sand there are no datings because of lack of shells and foraminifera.

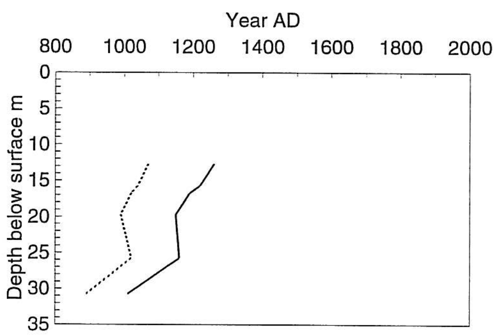

Fig. 14. Skagen 3 boring. Results of AMS ^{14}C-datings from the "Odde"sand (Nielsen et.al., 1994).

6. CREEP

6.1 *Moust Jacobsen's model*

Moust Jacobsen (Moust Jacobsen, 1992) has set up a model to separate creep and consolidation deformations during the consolidation process.

Moust Jacobsen assumed the consolidation and creep to be simultaneous, and has described the creep as

$$\varepsilon_{cr} = Q_s \log(1 + \tfrac{t_r}{t_b}) \qquad (1)$$

Q_s = rate of creep for $\sigma' \geq \sigma'_{pc}$

t_r is the real time passed

t_b is a reference time

If the sample is under constant stress from a time t_A to a time $t_A + t$, the additional creep is

$$\Delta\varepsilon_{cr} = Q_s \log(1 + \tfrac{t}{t_A + t_b}) \qquad (2)$$

and

$$\Delta\varepsilon_{cr} \sim Q_s \log(1 + \tfrac{t}{t_A}) \text{ if } t_A >> t_b$$

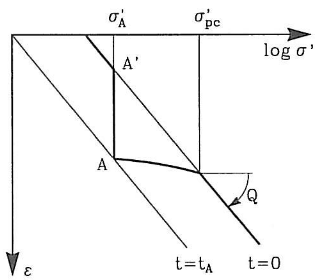

Fig. 15. Behavior of sligtly preconsolidated clay (Bjerrum, 1967).

t_A is the creep age, an age which will be reduced by any new loading (Bjerrum, 1967).

For a normally consolidated soil the creep age has often been assumed to be the geological age.

6.2 *Creep deformations*

In a curve described by (1), t_b is seen to be the additional time which turns the curve into a straight line in a logarithmic scale. t_b might therefore represent the creep time during the consolidation process, and the minimum value for t_A if the consolidation process is completed.

Assuming that the high sedimentation rate of the "Odde"sand from AD 1000 to AD 1200 has reduced the creep age to zero, corresponding to a creep age today of about 800 years the present creep rate is less than:

$$\Delta\varepsilon_{cr} = Q_s \log(1 + \tfrac{1}{800}) = Q_s \times 5{,}4 \times 10^{+4}\%$$

which gives a creep rate of about 0.2 mm/year for the total Holocene layer.

If the creep age is reduced to only 300 years, the creep rate is less than 0.5 mm/year.

Many uncertainties about creep still exist, and especially about the correspondence between the values determined in the laboratory and the real values.

Moust Jacobsen's model makes it possible to separate creep and consolidation by subtraction of the creep curve from the time settlement curve in the laboratory tests. Consequently the determination of the primary curve is improved and a value for the creep age for every load step is obtained. Based on this, an estimation of the state of consolidation is possible.

The actual oedometer tests have been carried out with the additional purpose to study the creep deformations and further investigations of the actual oedometer tests are in progress.

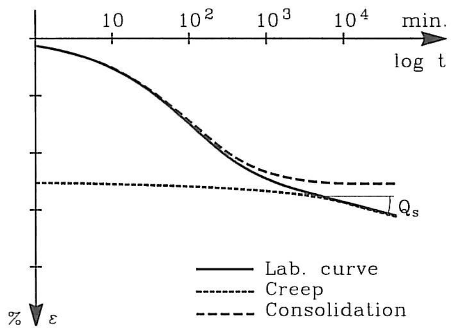

Fig. 16. Separation of creep and consolidation for a soil in a normally consolidated state.

7. CONCLUSION

The results of the geotechnical investigations in the Skagen 3 boring have indicated that the consolidation process in the Holocene silt and clay sediments caused by the sedimentation of the "Odde"sand is completed.

Based on an $OCR \geq 1$ and the values of the coefficient of consolidation, c_k, determined in the laboratory for the samples of clay, it is further concluded, that the actual drainage path in the clay sediments is smaller than half the total thickness of the clay deposits and that the sedimentation of the "Odde"sand must have been nearly finished some hundred years ago.

The AMS ^{14}C-datings have shown a very rapid sedimentation of the lower 18 m of the "Odde"sand. Datings of the upper 12 m sand are necessary to improve the modelling of the consolidation process.

The size of the creep rate is very dependent on the creep age and many uncertainties still exist about the correspondence between the values determined in the laboratory and the real values.

Moust Jacobsen (Moust Jacobsen, 1992) has set up a model to separate creep and consolidation in the laboratory tests. Based on this model further investigations of the actual oedometer tests are in progress in an attempt to improve the understanding of creep.

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